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Next 2 Page(s) In Document Denied

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# A NEW PRINCIPLE IN THE CONTROL OF A CURRENT IN SEMI-CONDUCTOR DEVICES

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The conductivity of a semi-conductor $\sigma$, in contrast to the conductivity of metals, may be expressed by the sum of two factors:

$$\sigma = \sigma_0 + \sigma_i \tag{1}$$

where $\sigma_0$ is the conductivity resulting from equilibrium carriers of charge, and $\sigma_i$ is the conductivity resulting from non-equilibrium carriers of charge.

Non-equilibrium carriers of charge can be introduced into a semi-conductor in a variety of ways, the most basic of which are radiation and injection by use of p-n junctions.

It is natural that the conductivity of a material changes depending on the amount of non-equilibrium carriers of charge introduced, and that this change, $\sigma_i$, can exceed the original equilibrium conductivity $\sigma_0$ with high levels of injection.

Large changes in conductivity can occur in samples with a relatively small initial equilibrium concentration of carriers of charge and also in those substances in which the life time of excess carriers of charge is relatively long.

Particularly significant changes in conductivity should take place in the event that the number of non-equilibrium carriers of charge appearing in the semi-conductor is multiplied. A mechanism to produce such multiplication is, for example, impact ionization.

We have studied the phenomenon of changes in conductivity in semi-conductors in conjunction with injected carriers of charge.

- 1 -

A suitable material for this purpose is germanium. In germanium it is relatively easy to produce p-n junctions, and with a proper selection of impurities it is possible to vary the initial conductivity within wide enough limits. A positive factor in experimental investigations is the fact that it is also possible to measure and vary the life time of excess carriers of charge in germanium, thus changing the number of recombination centers, traps, and the temperature of the material.

Selecting a proper range of temperatures for investigation of the germanium sample with definite centers of impurities, it is possible to vary the initial conductivity over a wide range by changes in temperature.

As is well known, atoms of antimony form donor levels located on the edge of the zone of conductivity with an energy of activation in the order of a hundredth of an electron volt. Atoms of gold form three acceptor levels and one donor level. The donor level is located at 0.05 electron volts from the top of the valence zone, the first acceptor level is located at 0.15 electron volts from the valence zone, and the second and third acceptor levels are at 0.2 electron volts and 0.04 electron volts from the bottom of the zone of conductivity.

In the relationship of the number of atoms of antimony $N'_{sb}$ and the atoms of gold $N_{Au}$, $\left(N_{Au} > N_{sb}\right)$ germanium possesses positive conductivity connected with the lower acceptor level. Since the energy of activation of the electrons to that level amounts to 0.15 electron volts in the region of temperatures from about $-50^{\circ}C$ and below, the concentration of excess carriers changes exponentially.

- 2 -

In the relationship $2 N_{Au} > N_{Sb} > N_{Au}$

the conductivity of the sample is negative, connected with the transfer of electrons from the second acceptor level into the zone of conductivity. With an energy of activation of this level of 0.2 electron volts, a large change in conductivity takes place in the presence of negative temperatures of the same order of magnitude, as well as for materials where $N_{Au} > N_{Sb}$.

It is possible to select that relationship between the concentrations of antimony and gold atoms so that the basic role in the conductivity of the sample will be played by levels with small energy of activation. However, materials with such concentrations are poorly suited for our purposes because the region of temperatures in which sharp changes in the concentration of carriers of charge may be observed is too low and too narrow.

An injection method utilizing p-n junctions was chosen for changing the concentration of non-equilibrium carriers of charge. For this purpose we used indium electrodes for p-type germanium or we used electrodes of tin with antimony for n-type germanium. The opposite electrodes were so chosen that they would not form injection junctions in the region of temperatures of interest.

The dimensions of the samples were varied in length only. The cross-section of all of them was about 3 or 4 $mm^2$.

Each sample prepared may be considered as a system consisting of a p-n junction with the resistance of the material in series with it (Figure 1).

If the resistance    is small, as is usually the case for germanium diodes, the current passing thru such a system may be well expressed by the

- 3 -

following formula:
$$I = \beta I_s \left( e^{\frac{U}{\beta KT}} - 1 \right) \tag{2}$$

where $U$ is the applied voltage, $I_s$ is the saturation current, and $\beta$ is a coefficient equal to 1 for small levels of injection and to 2 for higher levels.

A reduction of the temperature of the material down to the temperature of liquid nitrogen does not produce notable deviations from this formula.

In the case of a sample of germanium with a partially filled lower acceptor level or a partially filled middle acceptor level, with a p-n junction the passage of current does not obey the above formula for all temperatures.

For room temperature the resistance of germanium is small and deviation from formula (2) is insignificant. However, as the temperature is lowered, the concentration of carriers of charge falls and the resistance of the germanium increases. In this case we can no longer disregard the fall of voltage on the germanium in comparison with the fall of voltage on the junction for the case of positive values of applied potential (positive current).

The relationship between current and applied voltage in this case will take the form
$$I = \beta I_s \left( e^{\frac{U - Ir}{\beta KT}} - 1 \right) \tag{3}$$

In this formula the resistance of the germanium $r$ is not constant, but depends on the amount of current.

As was shown in reference /2/, when the voltage applied to the sample is increased at a lowered temperature in the positive direction the current first rises weakly, and then at a certain voltage $V_c$ (the breakdown voltage), the current suddenly sharply increases and the voltage simultaneously falls. (Figure 3, 9-12 in reference /2/)

- 4 -

The possibility of two conditions of conductivity of a diode was first noted by Tyler (Reference /3/) using samples of diodes prepared of germanium with impurities of iron, and called by him "injection breakdown".

After breakdown the relationship between the current and the voltage, as we have noted, is described by a formula of type $(2)$ and not by $(3)$. Therefore, the resistance $r$ becomes negligibly small.

As we have shown in reference /2/, the phenomenon of injection breakdown can only occur in the event that the conductivity of germanium connected with excess carriers of charge injected into it rises faster than linearly with respect to the rise of the current passing thru the sample. That is, $\sigma_i = a I^\gamma$ where $\gamma > 1$ .

Since $\sigma_i$ is proportional to the concentration of excess carriers of charge, for example, $c$ , and the latter is connected with the quantity of carriers of charge injected, $F_i$ , then

$$p_i = F \tau_p$$

where $\tau_p$ is the life time of the carriers. Since $F_i$ is proportional to the current injected, $I$ , the conductivity, $\sigma_i$ , may then be expressed by the following:

$$\sigma_i = q p_i \mu_p = q P_i \tau_p = a I \mu_p \tau_p$$

It is apparent that $\sigma_i$ may change more rapidly than linearly as a result of changes in current only if the mobility or the life time, or both these quantitites together change as the current varies.

The mobility $\mu_p$ can not change greatly for those values of current present before breakdown. Therefore, the mechanism of the breakdown must be located in the dependence of the life time on the strength of the current. The singularity of this dependence consists of the fact that it applies only beginning with a certain value of current.

An examination of the ▮▮▮▮ ▮▮▮▮▮▮ of the voltage $V_c$ at which breakdown occurs leads to the conclusion that the breakdown voltage $V_c$ rises almost exponentially with a reduction in the temperature (Figure 2). This fact indicates that for a given material the pre-breakdown current densities should be all approximately the same. An evaluation of these currents using oscillograms has confirmed this conclusion.

The character of dependence of the life time of the carriers of charge on their concentration according to Shockly and Read (Reference /4/) is shown on Figure 3.

As may be seen from this figure, the dependence of $\tau_p$ on $r_i$ is closely similar to that which is necessary to explain the breakdown phenomenon.

A change in the thickness of the material produces a considerable change in the value ⎿ for the same temperature. However, the strength of the pre-breakdown current changes in such materials only weakly.

From this it is evident that all conditions affecting the dependence of $\tau_p$ on the injection current can produce a displacement in either direction of the value of the breakdown voltage $V_c'$ .

Experiments we have carried out in this connection have shown that the quantity $\tau$ depends on the intensity of the radiation of the material and also under some conditions on the strength of the magnetic field.

V. I. Stafeev has shown (Reference /5/) that in a real semi-conductor diode with a fixed crystal thickness the strength of the current and the voltage applied for the case of large levels of injection ( $p_\lambda \gg r_c$ ) are related by the following equation:

$$I = I_c \, e^{\frac{b}{2\kappa T}} ,$$

- 6 -

where $c = 2 \frac{b \cdot ch \frac{L}{d}}{b+1}$ , $d$ is the thickness of the slice, $b$ is the ratio of mobility, $L = l_d \sqrt{\frac{2b}{b+1}}$ , and $l_d$ is the carriers' diffusion length.

The quantity $I_c$ depends completely on the parameters of the semi-conductor, and on $d/L$ among them. This dependence on $d/L$ is of the same order of magnitude as the dependence of $C$ . Since $C$ is part of the exponent of the formula above, changes in current $I$ are determined primarily by changes in $C$ . Thus, it may be easily seen that for sufficiently large values of $d/L$ , $C$ is related to the life time of the carriers of charge by the expression

$$C \simeq c \frac{\frac{d}{\sqrt{D_p \tau_p}}}{1}$$

Therefore, the current thru such a material depends strongly on the changes of $\tau_p$ in accordance with the following equation,

$$I = I_c e^{\frac{\frac{d}{\sqrt{D_p \tau_p}}}{\tau_p}}$$

The volt ampere characteristic curve computed using this formula is shown as Figure 4.

It is evident that the influence of a change in $\tau_p$ on the breakdown voltage is a certain new principle upon which to base the construction of a series of new semi-conductor devices.

## References

1. W. C. Dunlap, Physical Review (71, 102, 1953; 91, 1282, 1953; 97, 614, 1956; 98, 1535, 1955; 100, 1629, 1955).

2. Lebedev, A.A., Stafeev, B. I., Tuchkevich, V.M. JTP, 26, 2131, 1956.

3. W. W. Tyler, Phys. Rev. 96, 226, 1954.

4. W. Shockly, W. I. Read, Phys. Rev. 87, 835, 1952.

5. Stafeev, V. I., JTP, 28, 1631, 1958.